THE UTILITY AND VALIDITY OF KINEMATIC GPS POSITIONING FOR THE GEOSAR AIRBORNE TERRAIN MAPPING RADAR SYSTEM

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JPL

GeoSAR

Outline

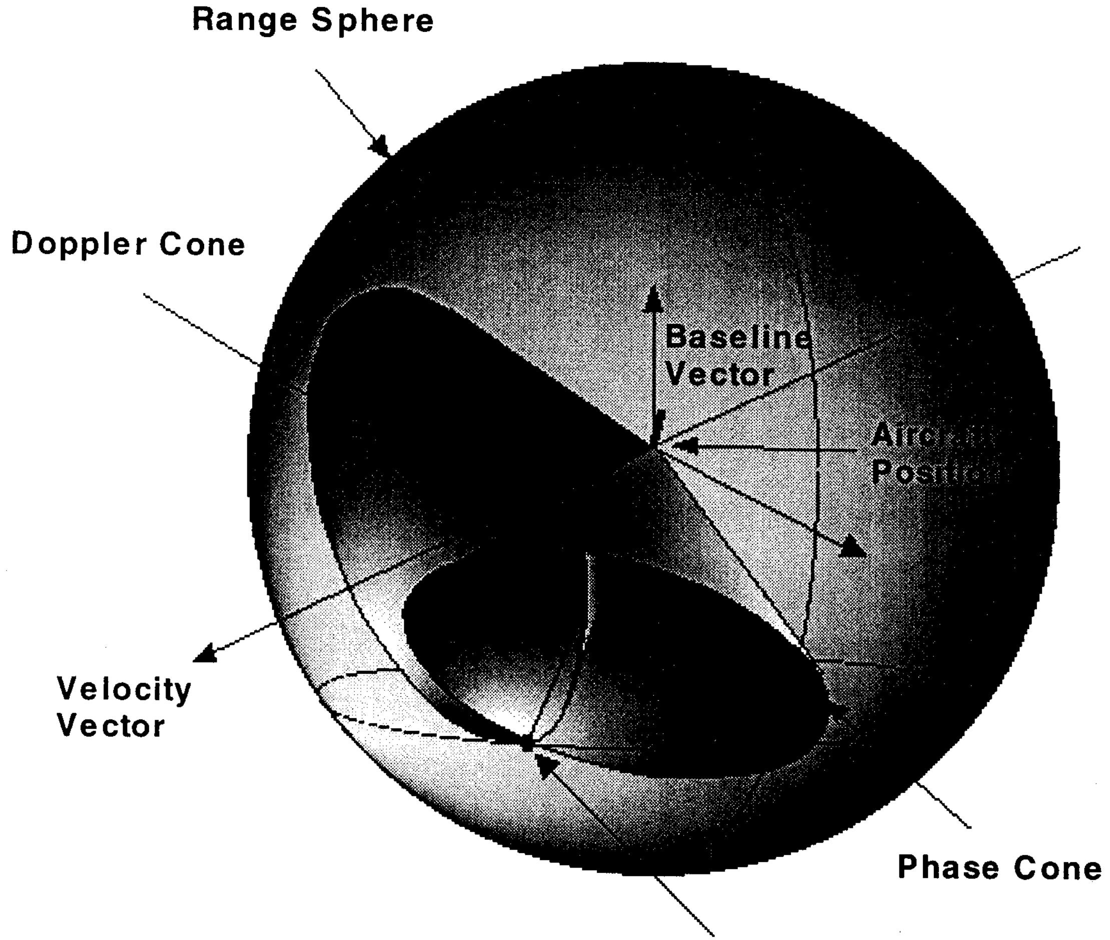
- Overview of GeoSAR Project
- Radar and Mapping Performance
- Aircraft Position Determination
- Radar Calibration
- Aircraft Position Verification
- Current Status and System Accuracy

Overview of GeoSAR

- Aircraft-based, interferometric synthetic aperture radar (SAR) system for topographic mapping.
  - Gulfstream II business jet
  - Day/night, all-weather, low-cost, commercial system
- Develop precision foliage penetration mapping technology based upon dual frequency, partially polarimetric, interferometric radar
  - X-band radar (λ=3 cm) for ground and tops of trees
  - P-band (UHF) radar (λ =86 cm) for ground and foliage penetration (H,V return)
- Produce true ground surface digital elevation models suitable for a wide variety of applications
  - Combination yields "true ground surface" (TGS)
- Consortium of three agencies, funding from DARPA and U.S. Army Corps of Engineers Topographic Engineering Center (TEC)
  - Caltech's Jet Propulsion Laboratory (JPL), Pasadena, CA
  - Calgis, Inc., Fresno, CA
  - California Department of Conservation (CalDOC)

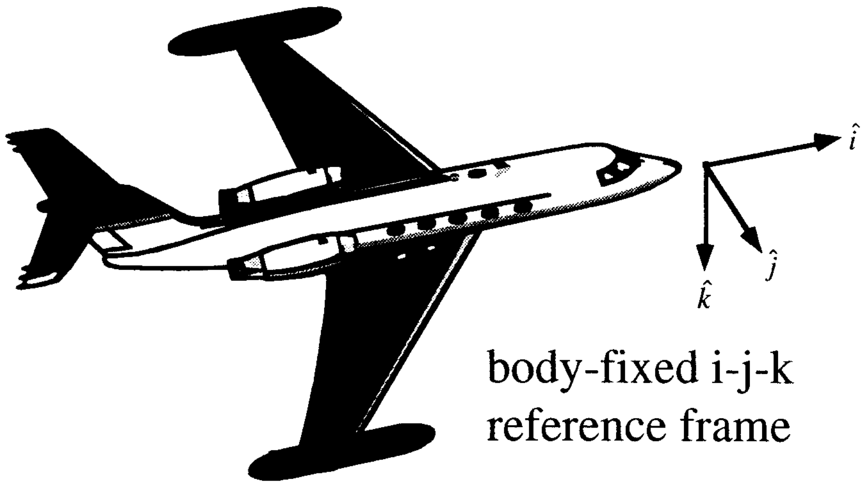
Department of Conservation

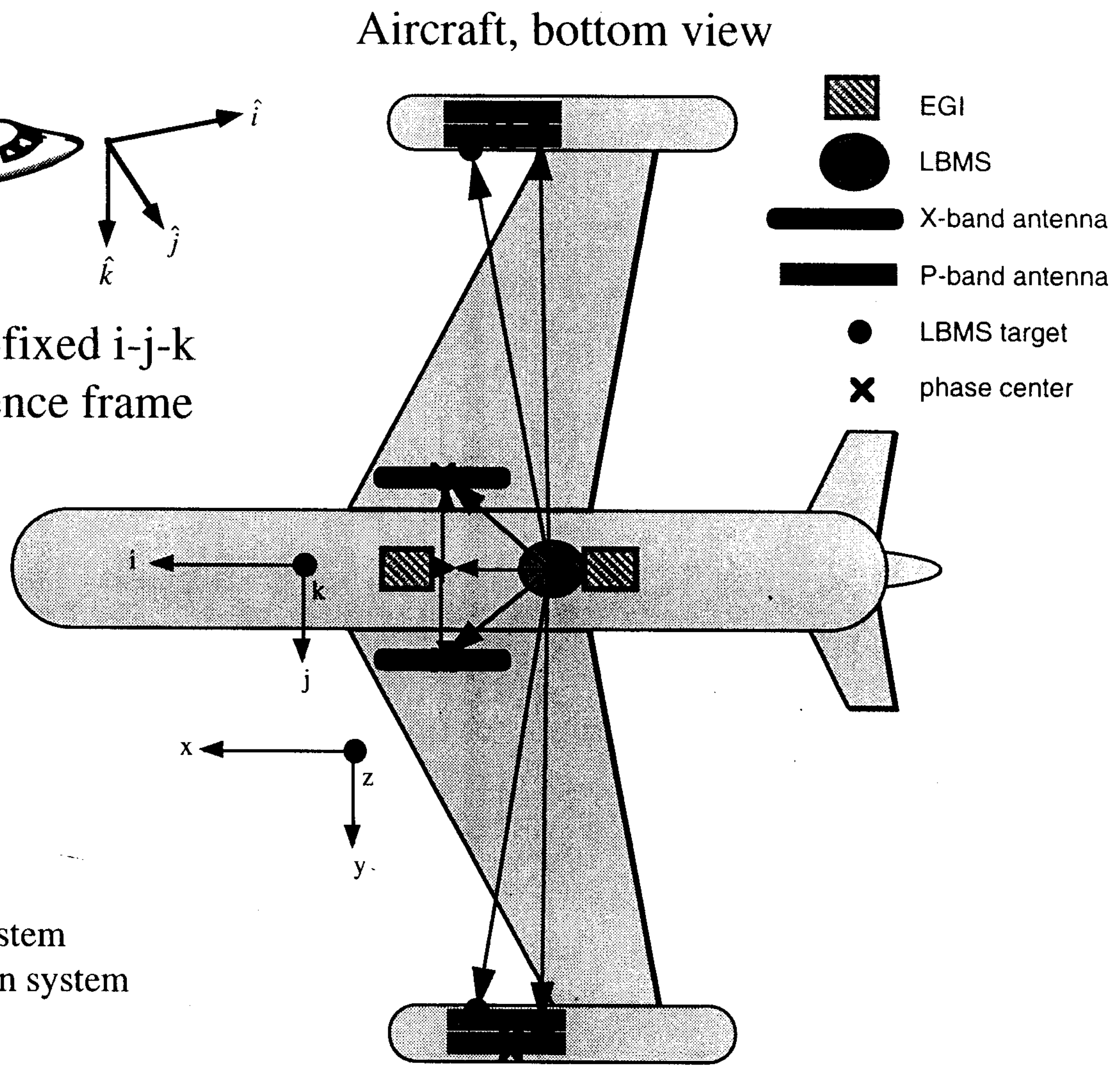
How SAR Interferometry Determines Position



Scatterer is at intersection of Range Sphere, Doppler Cone and Phase Cone

Aircraft System Illustration





LBMS - laser baseline measurement system
EGI - embedded GPS inertial navigation system

The GeoSAR Aircraft

Radar and Mapping Performance

- Height Accuracy (averaged over swath)
  - X-band height relative accuracy at 0.5 m level
  - P-band height relative accuracy of 1-2 m
  - Absolute errors (biases, longer-wavelength errors) expected to be 0.5-1 m greater
- Ground Resolution
  - Standard output posting (pixel spacing) of 5 meters
  - 1-meter resolution possible
- Planimetric accuracy (averaged over swath)
  - 1-4 meter, depending on bandwidth, aircraft height, etc.
- Areal Coverage
  - Two sided data collection, each side imaging a 10 km wide swath
  - Diverse modes: P-band ping-pong, P-band single baseline, P-band polarimetric, X-band data

Aircraft Position Determination

- High accuracy platform position and orientation required
  - Position to ~ 10 cm, altitude to ~ 25 cm
  - Attitude (yaw, pitch, roll) to ~ 15 arc seconds
  - 3-D Position => planimetric accuracy, DEM height accuracy
  - Attitude and interferometric baseline => cross-track position accuracy
  - Velocity => along track and vertical accuracy
  - IfSAR: along-track resolution of 50 cm, cross-track resolution of 1 m, oversampling of point targets to get ~10 cm positioning
- Calibration of many effect required, e.g.,
  - EGI biases
  - Range delays
  - Baseline corrections

Position Measurement Systems

- Honeywell Embedded GPS Inertial Navigation Units (EGI)
  - Precise attitude and velocity, rough positions.
- Ashtech Z12 GPS receiver
  - Precise positions in differential mode with nearby ground station.
  - PNAV software
- Lase Baseline Measurement System
  - Baseline length and attitude
- Kalman Filter used to estimate aircraft state
  - Combines position and velocity data
  - Accounts for varying uncertainties and temporal spacing
- Ground-based relative position measurements performed
  - Accurate to several centimeters or better
- Examples of EGI, dGPS, Kalman filtered positions

Ashtech Z-12 Data Processing

- Processing performed by Calgis, Inc.
- Ground receiver located within ~100 km of data take
- Turnaround time of a few hours after downloading both sets of data.
- Ashtech PNAV kinematic positioning software used
- Anticipated accuracy of ~ 10 cm or better.

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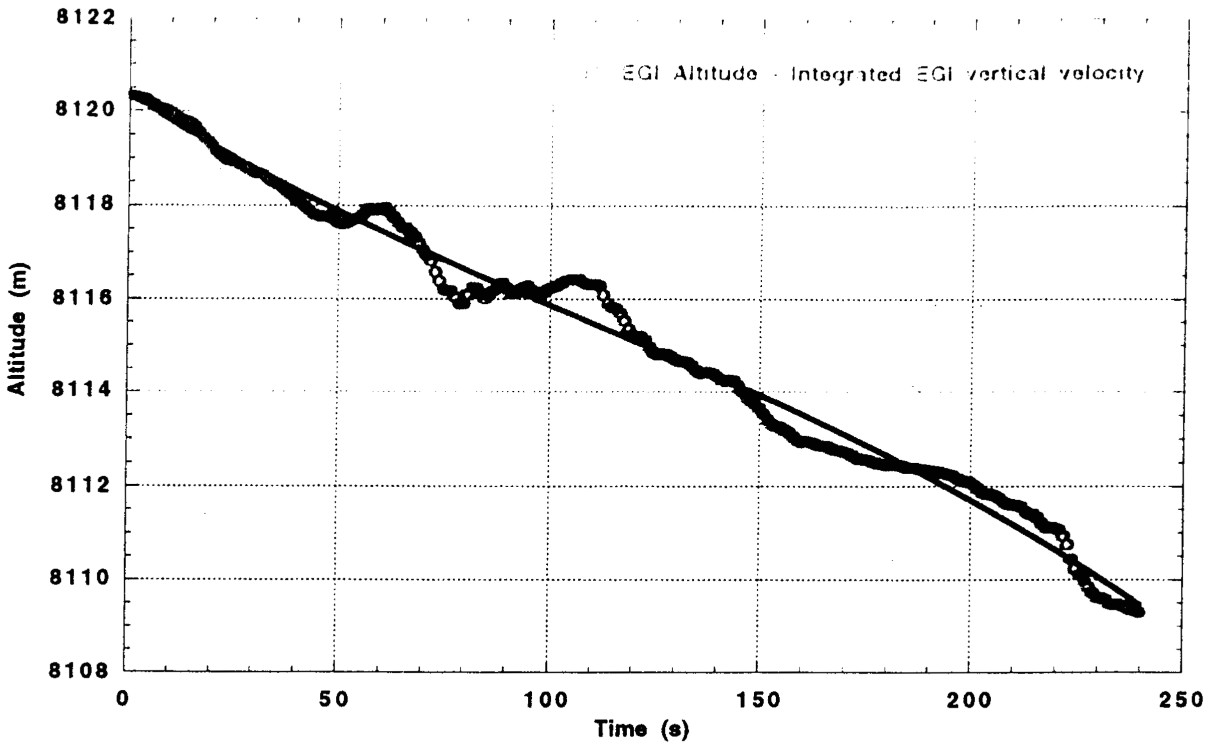
Comparison of EGI Altitude measurements (EO-17) with integrated EGI vertical velocity



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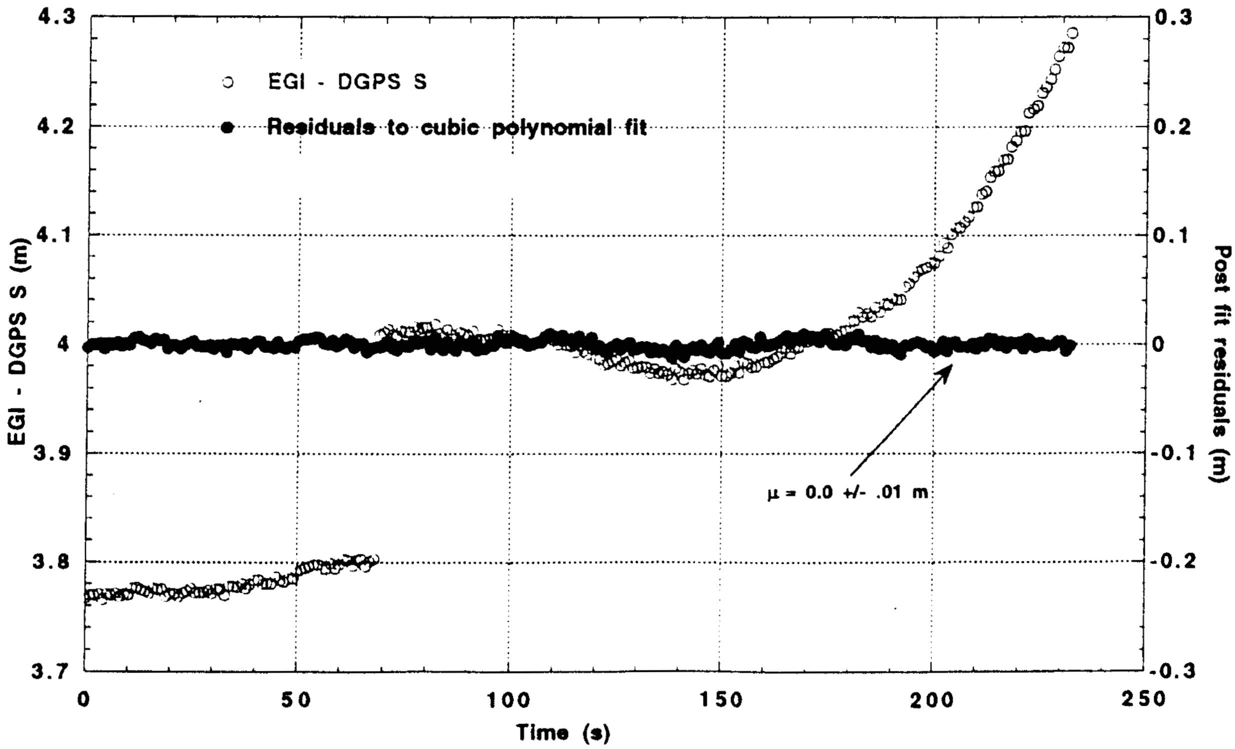
Comparison of High Rate EGI Position Measurements with Differential GPS Estimates



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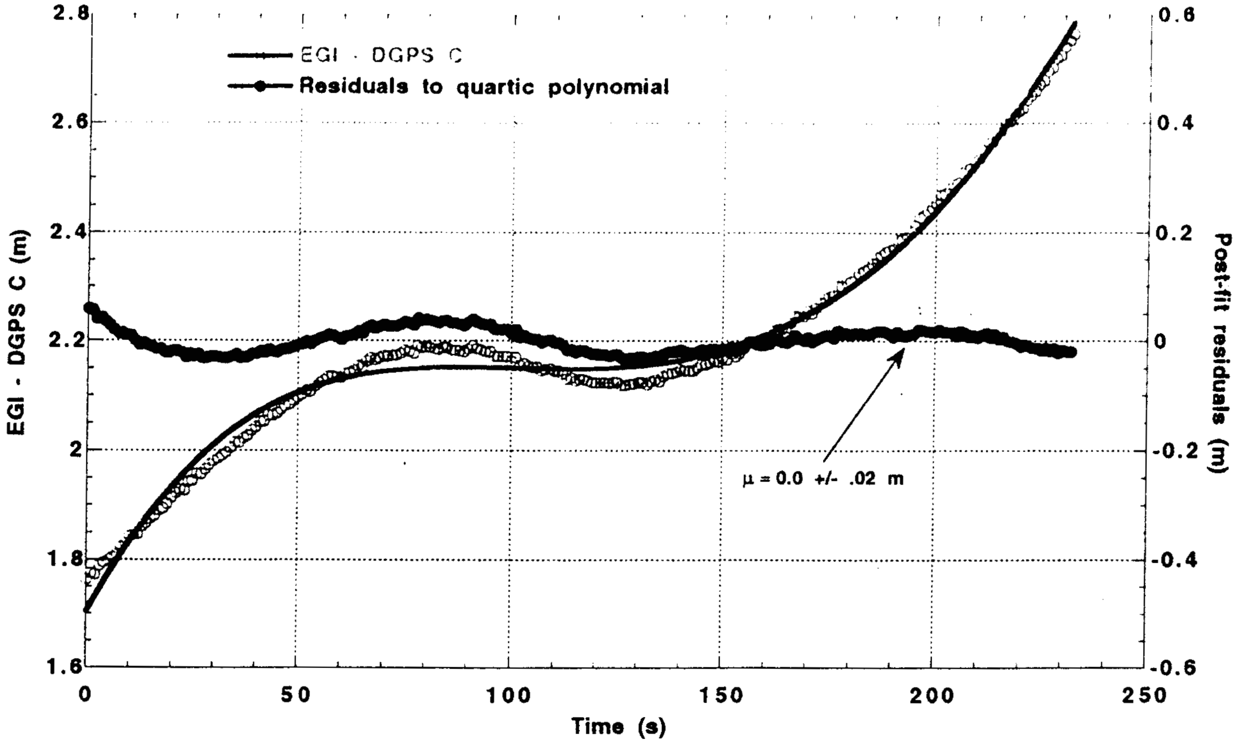
Comparison of High Rate EGI Position Measurements with Differential GPS Estimates



JPL Presentation to Lockheed Martin TDS

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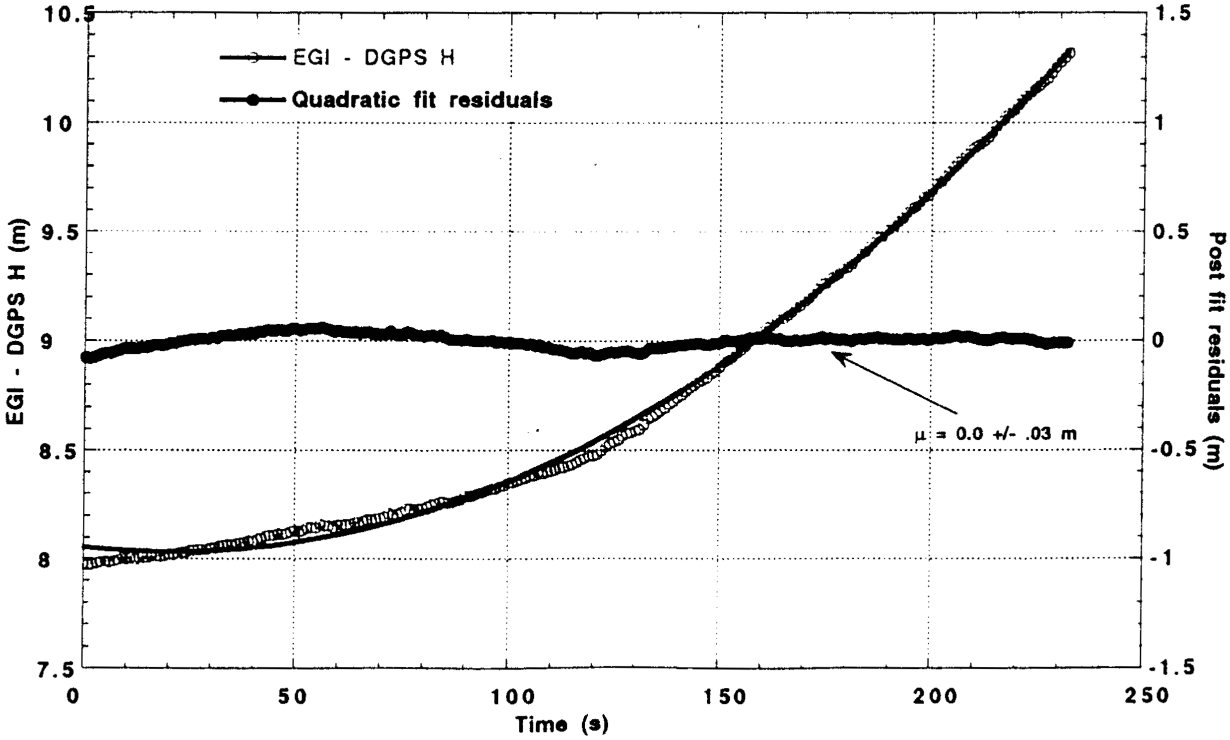
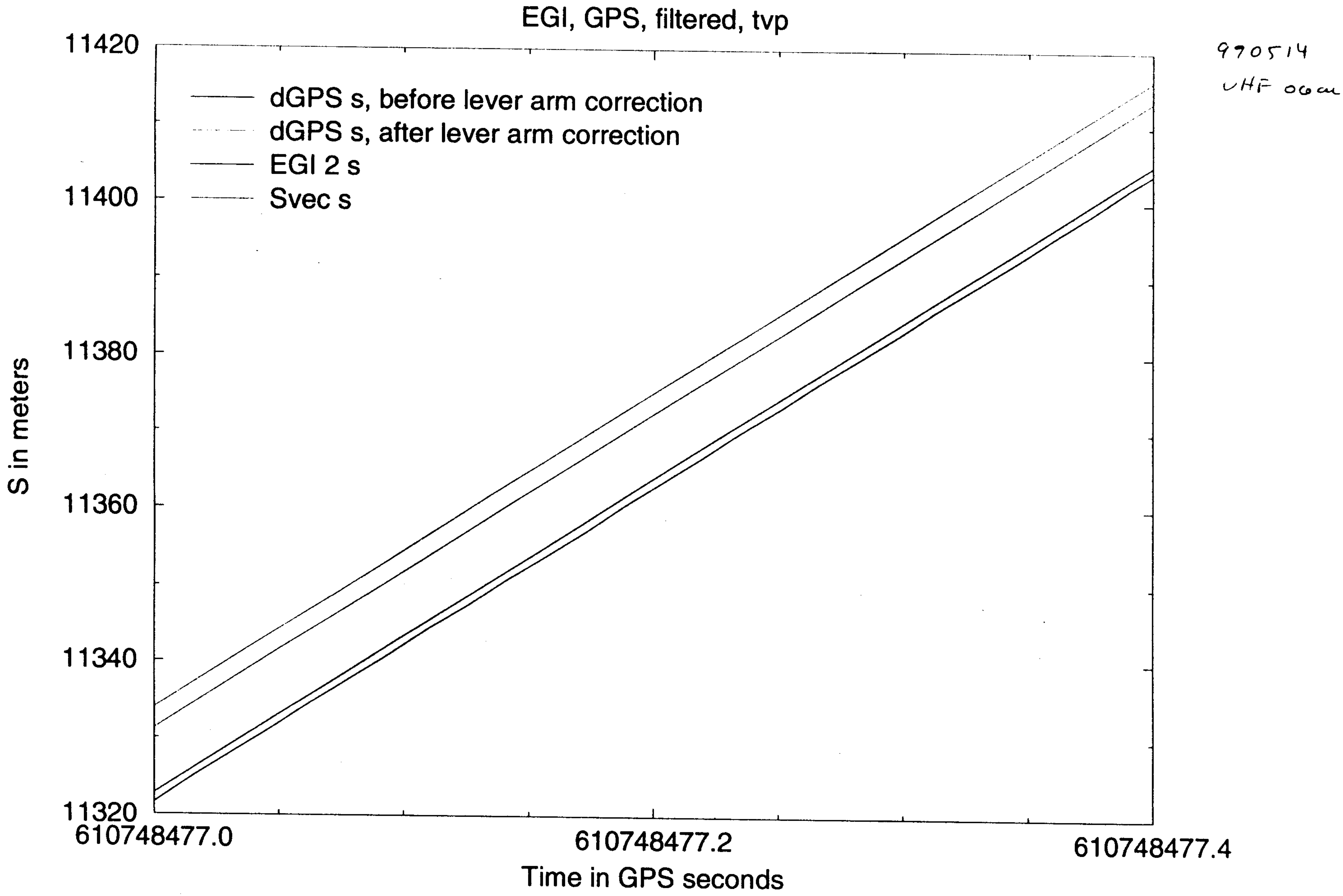
Comparison of High Rate EGI Position Measurements with Differential GPS Estimates



SCH Position Comparison



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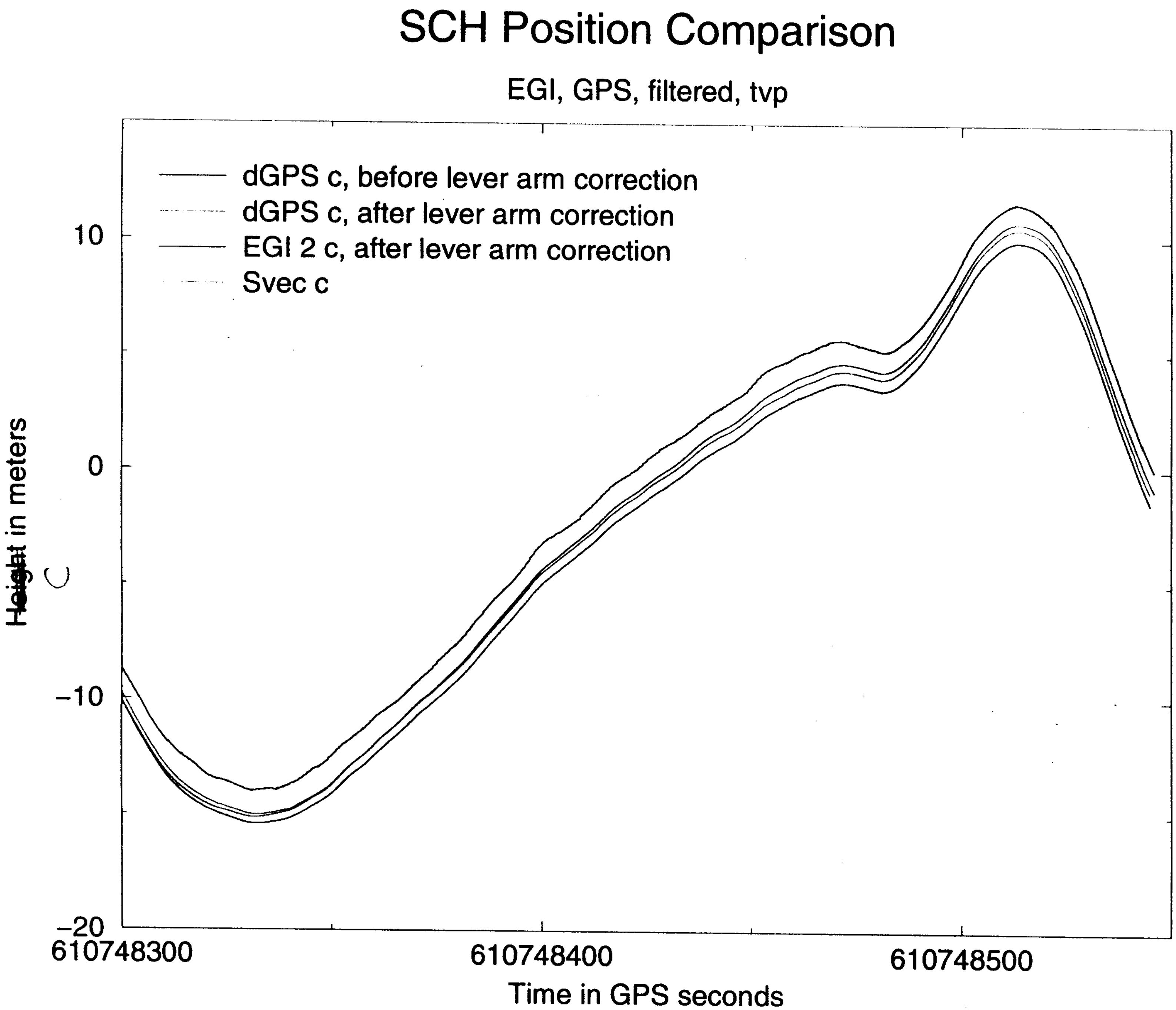

SCH Position Comparison

EGI, GPS, filtered, tvp

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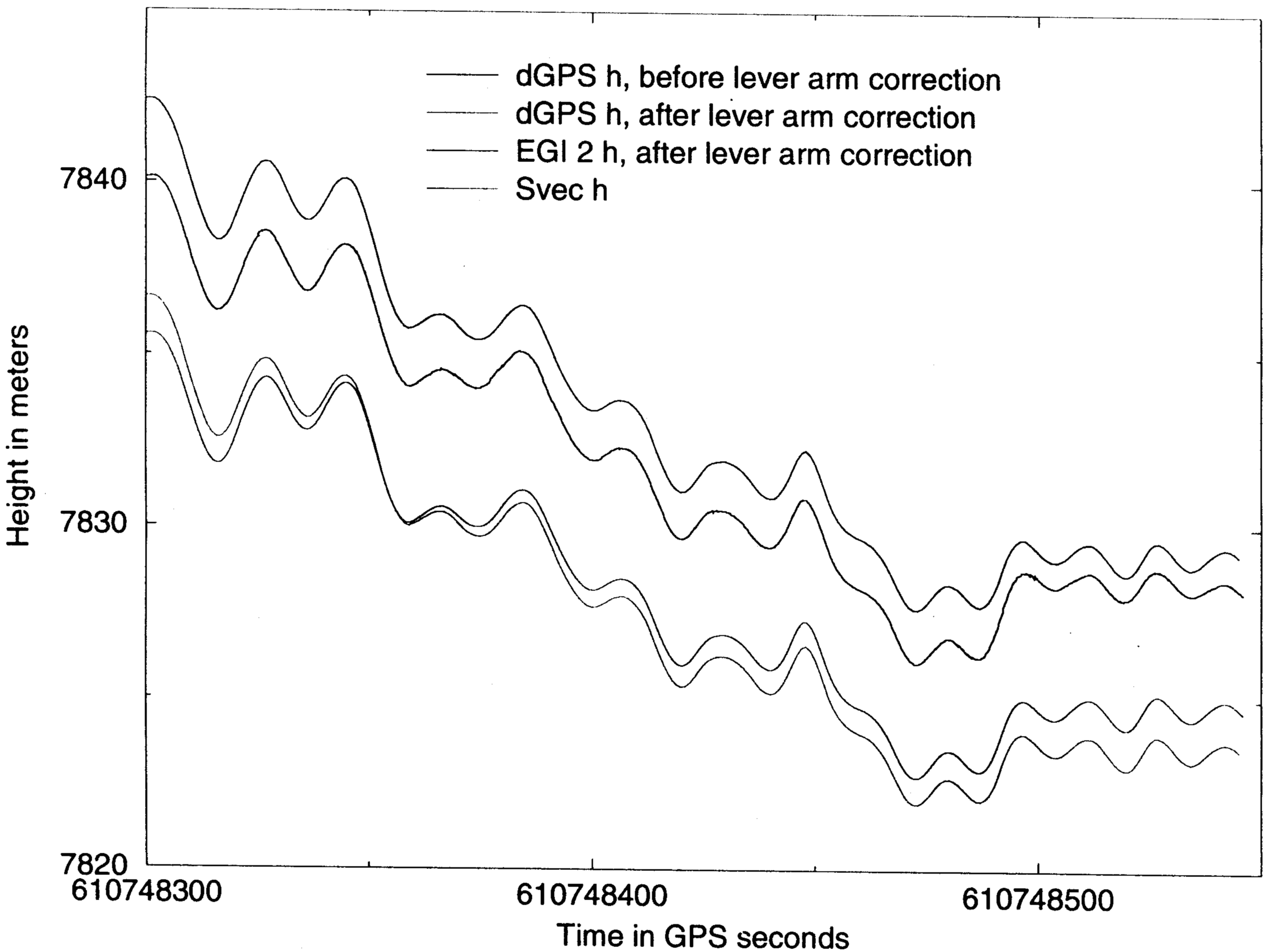
UHF ocean



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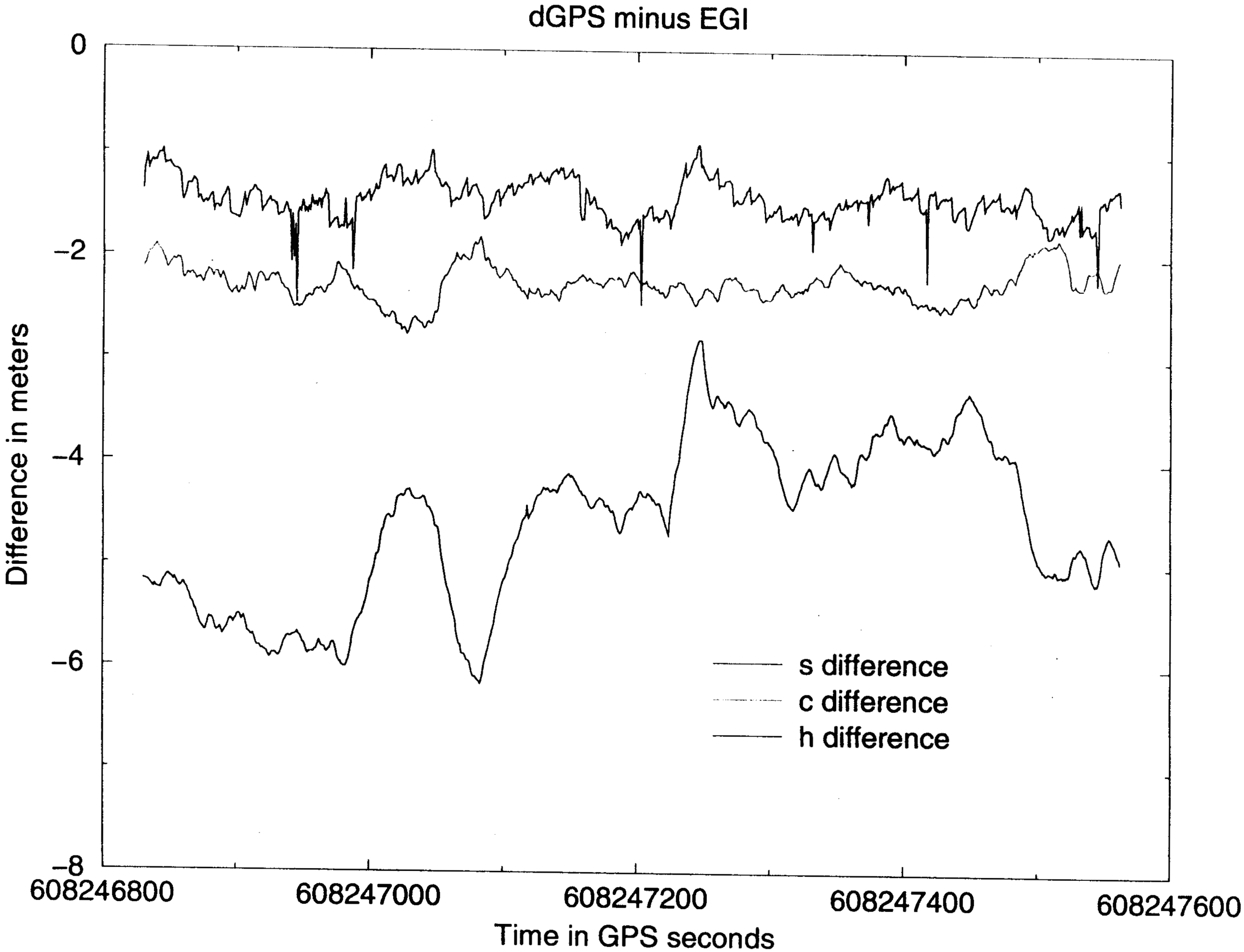
Blended EGI vs. dGPS Positions



Blended EGI vs. dGPS Positions

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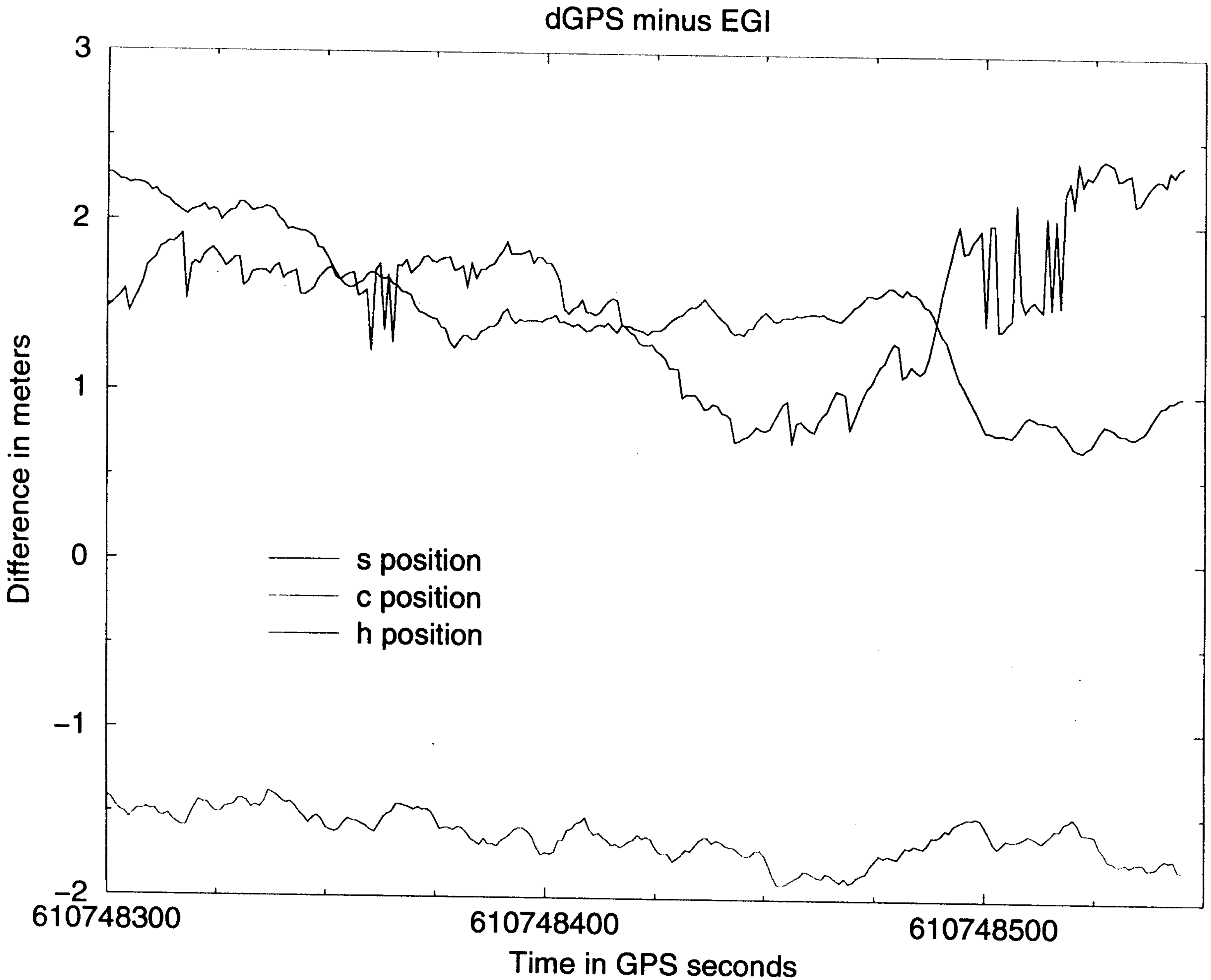


Parameters to be Estimated

- Five common range delays: UHRpp, UHLss, XNLpp, XNRss, and XPRss.
- Ten differential time delays: UHRps-UHRpp, UHRss-UHRpp, UVRss-UHRss, UHLsp-UHLss, UHLpp-UHLss, UVLpp-UHLpp, XNLps-XNLpp, XPLss-XPLpp, XNRsp-XNRss, and XPRpp-XPRss.
- Three dimensional baseline corrections for the four physical baselines: the UHF Left, the UHF Right, the X Left, and the X Right.
- Phase and amplitude corrections for all 15 distinct logical channels.
- Eight interferometric phase screens: URP, URS, XRP, XRS, ULP, ULS, XLP, and XLS.
- Yaw and pitch EGI biases for both EGIs.

Error in Platform Position

$$\frac{\partial \vec{T}}{\partial P_s} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

$$\frac{\partial \vec{T}}{\partial P_c} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{2}$$

$$\frac{\partial \vec{T}}{\partial P_h} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{3}$$

P_s, P_c, and P_h are the three components of the aircraft position, $\vec{P}$, in the along track direction, in the across track direction, and in height, respectively. $\vec{T}$ is the target position, ρ is the range to the target, and $\hat{l}_{sch}$ is the look direction to the target. The three component vector in square brackets indicates the s, c, and h components.

Intuitively, an error in the aircraft position merely translates the entire scene. This is expected since $\vec{T} = \vec{P} + \rho \hat{l}_{sch}$.

Error in the Range

$$\frac{\partial \vec{T}}{\partial \rho} = \begin{bmatrix} \cos(\beta) \\ \mu \sin(\theta) \\ -\cos(\theta) \end{bmatrix} = \hat{l}_{sch} \tag{4}$$

where

$$\mu = \sqrt{1 - \left(\frac{\cos(\beta)}{\sin(\theta)} \right)^2}, \tag{5}$$

β is the angle between the aircraft velocity and the look direction, and θ is the look angle.

Error in Baseline Length

$$\frac{\partial \vec{T}}{\partial B} = \frac{\rho}{B} \left(g_{tan} + \frac{\tan(\kappa)\cos(\beta)}{g_{cos}} \right) \left[\begin{array}{c} 0 \\ -\cos(\theta) \\ -\mu\sin(\theta) \end{array} \right] \tag{6}$$

where

$$g_{tan} = \frac{\cos(\alpha)\sin(\theta)\mu - \sin(\alpha)\cos(\theta)}{\sin(\alpha)\sin(\theta)\mu + \cos(\alpha)\cos(\theta)}, \tag{7}$$

$$g_{cos} = \sin(\alpha)\sin(\theta)\mu + \cos(\alpha)\cos(\theta), \tag{8}$$

α is the baseline roll angle, B is the baseline length, and κ is the baseline yaw angle.

Error in Baseline Roll Angle

$$\frac{\partial \vec{T}}{\partial \alpha} = \rho \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \tag{9}$$

Error in Baseline Yaw Angle

$$\frac{\partial \vec{T}}{\partial \kappa} = \rho \left(\tan(\kappa) g_{tan} + \frac{\cos(\beta)}{g_{cos}} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \tag{10}$$

Error in Phase

$$\frac{\partial \vec{T}}{\partial \phi} = \left(\frac{-\lambda \rho}{a 2 \pi B g_{cos} \cos(\kappa)} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \tag{11}$$

where a is 1 or 2 for ping-pong or single transmit.

Fitting for the Corrections

$$\frac{\partial \vec{T}}{\partial \vec{P}}\Delta \vec{P} + \frac{\partial \vec{T}}{\partial \rho}\Delta \rho + \frac{\partial \vec{T}}{\partial B}\Delta B + \frac{\partial \vec{T}}{\partial \alpha}\Delta \alpha + \frac{\partial \vec{T}}{\partial \kappa}\Delta \kappa + \frac{\partial \vec{T}}{\partial \phi}\Delta \phi = \Delta \vec{T} \quad (12)$$

We know the derivatives, and we can measure the target postion error $\Delta \vec{T}$ for each target. Therefore we can solve the Least Squares technique for the error in the platform postion $\Delta \vec{P}$, the error in the range $\Delta \rho$, the error in the baseline length ΔB, the error in the baseline roll angle $\Delta \alpha$, the error in the baseline yaw angle $\Delta \kappa$, and the error in the phase $\Delta \phi$. We use Singular Value Decomposition to evaluate the actual errors.

Slant Plane Corrections

The error of the range of a target is given by

$$\frac{\partial \rho}{\partial P_s}\Delta P_s + \frac{\partial \rho}{\partial P_c}\Delta P_c + \frac{\partial \rho}{\partial P_h}\Delta P_h + \frac{\partial \rho}{\partial \tau}\Delta \tau = \Delta \rho, \tag{13}$$

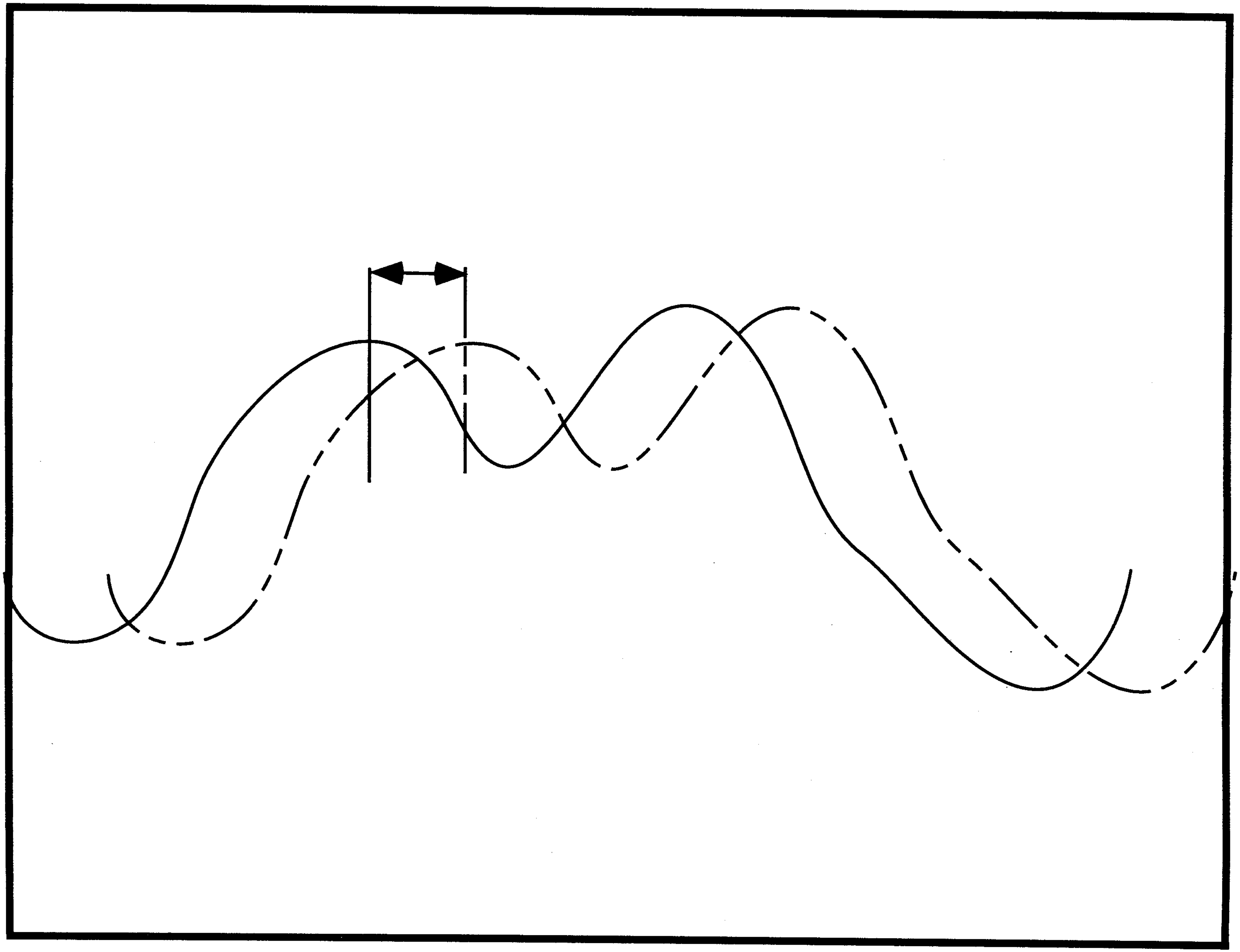
where

$$\begin{array}{ll} \frac{\partial \rho}{\partial P_s} = \cos(\beta), & \frac{\partial \rho}{\partial P_c} = \mu \sin(\theta), \\ \frac{\partial \rho}{\partial P_h} = -\cos(\theta), & \frac{\partial \rho}{\partial \tau} = 1, \end{array} \tag{14}$$

and τ is the common range delay. The location error in range of each target is measured, and equation (13) is solved using singular value decomposition to determine the platform position errors and range errors.

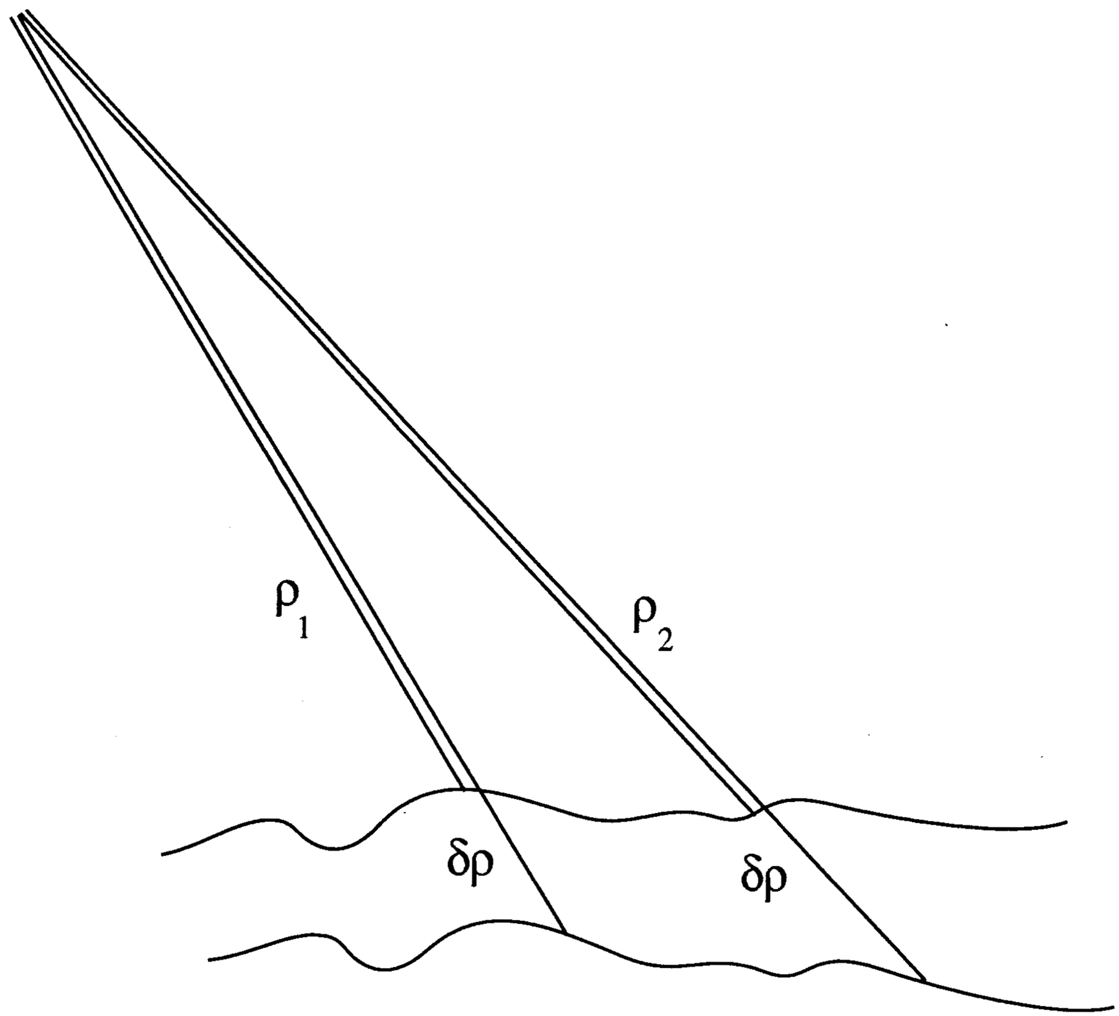
Differential Time Delay

- The differential time delay is the difference between the time delays for two channels.
- The differential time delay can be determined by examining the time difference when two channels view common objects in the slant plane image. This method is accurate to about 0.2 pixels. The accuracy is limited by the ability to resolve the position of the target to a fraction of a pixel and by the number of targets to average.
- Alternately the differential time delay can be determined by cross correlating the slant plane images of the two channels. This second method is accurate to about 0.05 pixels. Cross correlations can be done throughout the image; no radar identifiable targets are required.



Common Range Delay

- The common range delay is the time delay for one of the two interferometric channels identified as the reference.
- The common range delay can be determined by examining the location in the slant plane image where a recognizable target of known location was imaged. This method is accurate to about 0.2 pixels. The accuracy is limited by the ability to resolve the position of the target to a fraction of a pixel and by the number of targets to average and the uncertainty in the aircraft position.
- Since the differential time delay can be calibrated more accurately than the common range delay, the calibration procedure is to calculate as many time delays as possible as differential time delays and as few as possible using the common range delay procedure.


ρ_1
ρ_2
$\delta\rho$
$\delta\rho$

Effects of INU Errors on GeoSARImagery

Parameter With Error	Error in Topography	Error in Height for Broadside Geometry
EGI Position	$\frac{\partial \vec{T}}{\partial \vec{P}_{EGI}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\frac{\partial z}{\partial h} = 1$
EGI Velocity	$\frac{\partial \vec{T}}{\partial v} = \frac{-\rho \cos(\beta)}{v g\cos(\theta,\alpha,\beta)\cos(\kappa)} \begin{bmatrix} g\cos(\theta,\alpha,\beta)\cos(\kappa) \\ -\sin(\alpha)\cos(\beta)\cos(\kappa) - \sin(\kappa)\cos(\theta) \\ \cos(\alpha)\cos(\beta)\cos(\kappa) - \mu\sin(\kappa)\mu\sin(\theta) \end{bmatrix}$	$\frac{\partial z}{\partial v} = 0$
EGI Yaw	$\frac{\partial \vec{T}}{\partial \kappa} = \rho \left(\tan(\kappa) g\tan(\theta,\alpha,\beta) - \frac{\cos(\beta)}{g\cos(\theta,\alpha,\beta)} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}$	$\frac{\partial z}{\partial \kappa} = 0$
EGI Roll	$\frac{\partial \vec{T}}{\partial \alpha} = \rho \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}$	$\frac{\partial z}{\partial \alpha} = \rho\sin\theta = \text{ground range}$
Calibration Error	$\frac{\partial \vec{T}}{\partial \rho} = \begin{bmatrix} \cos(\beta) \\ \mu\sin(\theta) \\ -\cos(\theta) \end{bmatrix}$	$\frac{\partial z}{\partial \rho} = -\cos\theta$

$$g\cos(\theta,\alpha,\beta) \equiv \sin(\alpha)\sin(\theta)\mu + \cos(\alpha)\cos(\theta) \qquad g\sin(\theta,\alpha,\beta) \equiv \cos(\alpha)\sin(\theta)\mu - \sin(\alpha)\cos(\theta)$$

$$g\tan(\theta,\alpha,\beta) \equiv \frac{g\sin(\theta,\alpha,\beta)}{g\cos(\theta,\alpha,\beta)} \qquad \mu \equiv \sqrt{1 - \left(\frac{\cos(\beta)}{\sin(\theta)}\right)^2}$$

θ = look angle α = baseline roll or tilt angle ρ = range β = baseline squint angle (broadside = $\pi/2$) κ = baseline yaw angle

Effects of INU Errors on GeoSAR Imagery (2)

INU-derived quantity	Error	Effect on s position	Effect on c position	Effect on h position
s position	5 meters	5 meters (1 pixel)	0	0
c position	2 meters	0	2 meters	0
h position	8 meters	0	0	8 meters
s velocity	1 cm/sec	0.2 meters	0	0
c velocity	1 cm/sec	0	0	0
h velocity	3 cm/sec	0	0	3 meters
yaw	12 arc sec	0	0.2 meters	0.1 meters
pitch	8 arc sec	0	0	0
roll	12 arc sec	0	0.6 meters	0.6 meters
common range effect	~ 10 m	0	0	10 meters

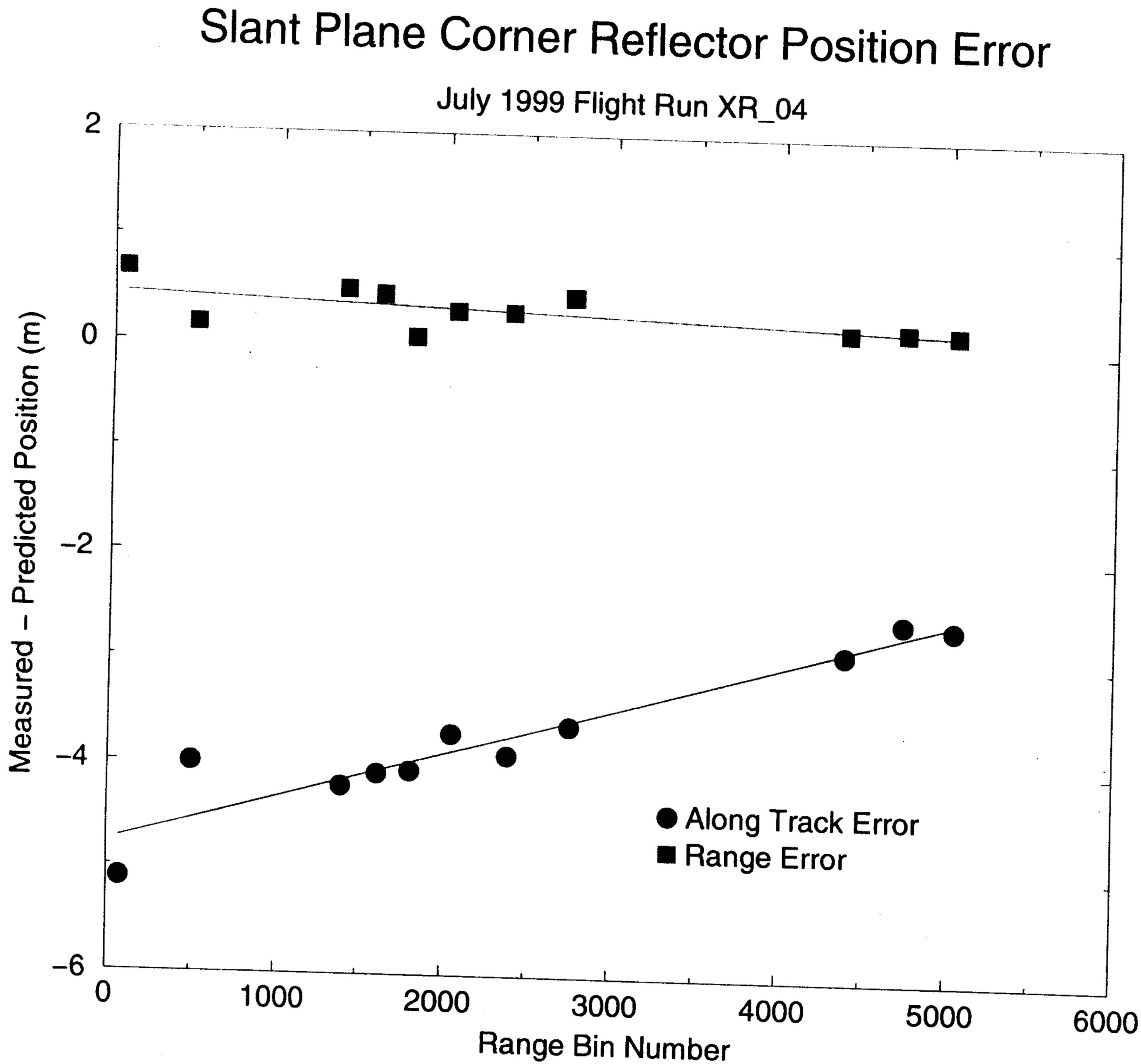
Notes: h-velocity effect comes through integrating the velocity to obtain height variability. The common range effect is the effect of a height error on the common range delay calibration, and the subsequent range error on the height estimates.

Summary

- ~1 pixel planimetric offsets due to EGI position uncertainty.
- several meters of vertical error due to EGI height uncertainty.
- dGPS reduces s/c/h position induced errors to 10-50 cm.

Radar Calibration summary

- GeoSAR radar must be fully calibrated to determine accurately platform position errors.
- Note that there is trade off between
  - Along-track positions and pulse timing offsets
  - Along-track positions and errors in positions of units (EGI, GPS antenna, etc.)
  - Cross-track positions and range delays
  - Cross-track positions and baseline errors
  - Height estimates and many error sources
- Errors are reduced by
  - using SLC (single-look comples) images from each antenna
  - two sided operation



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Current Status and System Accuracy

- GeoSAR aircraft undergoing radar test flight
- X-band radar well proven and mostly calibrated
- P-band radar not fully proven, not calibrated
- System capable of verifying aircraft position at ~25 cm or better level.
- More calibration flights will allow separation of errors and better definition of errors in GPS systems.